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Light Water Reactor Sustainability (LWRS)

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U.S. Department of Energy

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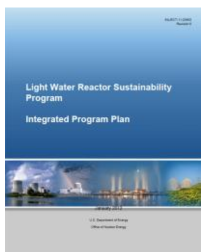
Objectives and Strategic Linkages

- **Program Goals**
  - Develop the fundamental scientific basis to understand, predict, and measure changes in materials and systems, structures, and components (SSCs) as they age in environments associated with continued long-term operations of the existing reactors
  - Apply this fundamental knowledge to develop and demonstrate methods and technologies that support safe and economical long-term operation of existing reactors
  - Research new technologies to address enhanced plant performance, economics, and safety.



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Technical Focus Areas

- **Nuclear Materials Aging and Degradation**
  - Develop scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants
  - Provide data and methods to assess performance of systems, structures, and components essential to safe and sustained nuclear power plant operation, providing key input to both regulators and industry
- **Advanced Instrumentation, Information, and Control System Technologies**
  - Develop, demonstrate, and deploy new digital technologies for instrumentation and control architectures and provide monitoring capabilities to ensure the continued safe, reliable, and economic operation of the nation's operating nuclear power plants
- **Risk-Informed Safety Margin Characterization**
  - Develop and demonstrate a risk-assessment method that is tied to quantification of safety margins
  - Develop advanced safety assessment tools that can enable a more accurate representation of a particular plant safety margin
- **Advanced Nuclear Fuels**
  - Develop high-performance, higher burn-up fuels with improved safety and economics
- **Systems Analysis and Emerging Issues**
  - Address high impact emerging issues such as potential back-fit of cooling towers
  - Review research needs in response to Fukushima lessons learned

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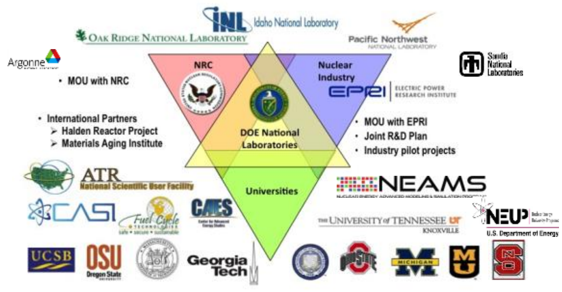
The LWRS Partners are Key to Our Success



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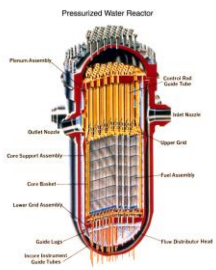
Materials Aging and Degradation

- Develop the scientific basis for understanding and predicting materials aging and degradation within components, systems, and structures
  - Reactor metals
    - Mechanisms of IASCC
    - High-fluence effects on RPV steel
    - Crack initiation in Nickel based alloys
  - Concrete aging and monitoring tools
  - Cabling aging assessment
  - Mitigation, repair, and replacement technologies including advanced Non-Destructive Evaluation (NDE) techniques

Key Deliverables:

- (2012) Expanded Materials Degradation Assessment
- (2014-2016) Mechanistic understanding for key materials and degradation modes and model capability for key core internal issues



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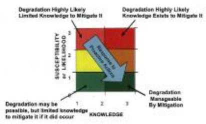
Materials Aging and Degradation tasks provide results in several ways

- ***Measurements of degradation:*** High quality data will provide key information for mechanistic studies, but has value to regulators and industry on its own.
- ***Mechanisms of degradation*:** Basic research to understand the underlying mechanisms of selected degradation modes will lead to better prediction and mitigation.
- ***Modeling and simulation*:** Improved modeling and simulation efforts have great potential in reducing the experimental burden for life extension studies. These methods can help interpolate and extrapolate data trends for extended life.
- ***Monitoring*:** While understanding and predicting failures are extremely valuable tools for the management of reactor components, non-destructive monitoring must also be utilized.
- ***Mitigation strategies*:** While some forms of degradation have been well-researched, there are few options in mitigating their effects. New technologies may overcome limits of degradation in key components and systems.

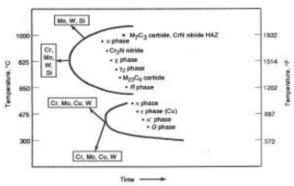
Expanded Materials Degradation Assessment (EMDA)

- **"Knowing the unknowns" is a difficult problem that must be addressed.**
- **This is a particularly difficult issue for such a complex and varied material/environment system.**
- **An organized PMDA approach is being employed.**
- **Together with the U.S. NRC, the LWRS Program is working to expand the initial PMDA activity (*NUREG/CR-6923)* to encompass broader systems and longer lifetimes**
  - Core internals and primary piping
  - Pressure Vessel
  - Concrete
  - Cabling



Will cast stainless steel aging be an issue for long-term operations?

- **EMDA has identified thermal aging as a long-term need**
- **Previous MDM identified a lack of data in this area (but no service failures)**
- **This is a new FY12 task**

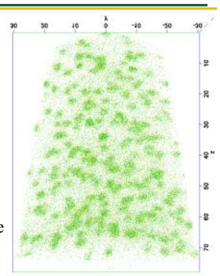


"Late Blooming Phases" (LBP) have been the focus of one key metals research task

Classical embrittlement of the reactor pressure vessel has been driven by rapid Cu-rich precipitate hardening

Early models (Odette et al.) predicted:

- Mn-Ni(-Si-Cu) LBP that can reach large volume fractions (f)
- LBP favored by lower T_{irr} and flux and higher Ni and Mn
- Low nucleation rates at low/no Cu require high fluence – viz. LBP
- Could lead to large embrittlement in low Cu steels previously thought to have little sensitivity to embrittlement



APT of ATR BR2 alloy 0.0 Cu-0.8Ni at 1 x 10^{21} nm/cm^2

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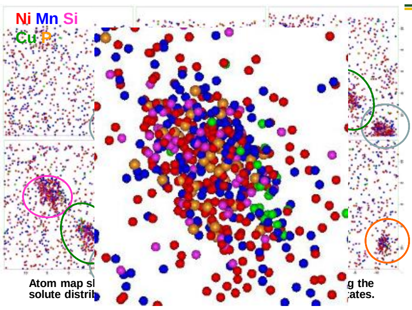
E6 surveillance weld: Atom maps - 1 nm slices



Fe (wt%)
0.08 Cu
1.58 Ni
1.46 Mn
0.54 Mo
0.21 Si
0.07 Cr
0.009 P
0.052 C

13.8 effective full power years

High 0.08%Cu, high fluence: 6.4 x10^{19} n cm^{-2}

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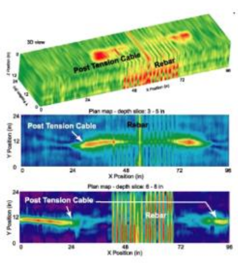
NDE development is being integrated with materials research

- **Continued work on crack and crack precursor detection development**
- **Developed NDE Roadmaps**
  - Concrete
  - Cables
  - Fatigue damage
  - Reactor pressure vessel
- **Roadmaps were assembled based on a variety of sources**
  - Assessed key degradation modes
  - Interacted with materials experts
  - Assembled an expert panel and hosted a workshop
- **Roadmaps are available on the LWRS website**



Ground Penetrating Radar

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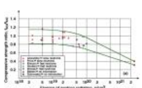
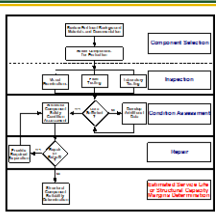
Concrete research is required to provide an objective assessment of useful life

USNRC-Related Activities

NUREG/CR-7111

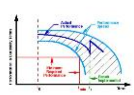


Irradiation Effects



LWRS Program

Nuclear Concrete Materials Database



Risk-Informed Guidelines for Evaluating Performance of Aged Concrete Structures

IAEA RILEM ACI 349 ASME Sec. XI NESCC

International/Technical Committees

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Nuclear Concrete Materials Database (NCMDB)

ORNL/TM-2011/296

Concrete coring to obtain samples for evaluating effects of aging and environmental stressors

- **Phase I of NCMDB has been completed and is on an internal server**
- **Data and information for populating the NCMDB are provided from literature sources and obtaining and testing samples from aged facilities**
  - Aging
  - Elevated temperature
  - Irradiation
  - Migration of hostile species (e.g., Cl^-, SO_4, CO_2)
- **Concrete irradiation damage working group formed**
  - Development of protocols related to removal and testing of irradiated concrete cores
  - Identification of potential sources of irradiated concrete cores

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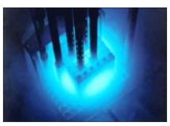
Cable Aging Degradation research has continued with a particular focus on thermal and irradiation effects



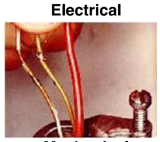
Radiation

Moisture

Electrical

Thermal

Water Tree Phenomena



Mechanical

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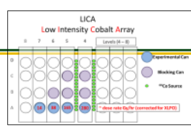
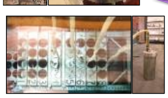
Cable aging research has focused on both service and lab materials

Finalized LICA Facility Updates



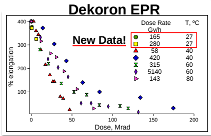
Performed Dosimetry and Updated Experimental Plan



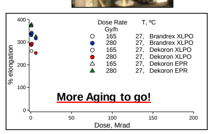
Initiated Long-Term Aging Experiments

Tensile Tested New and Aged Specimens

Dekoron EPR



Analyzed Aging Data



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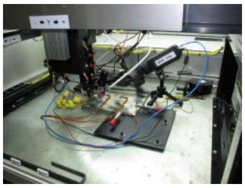
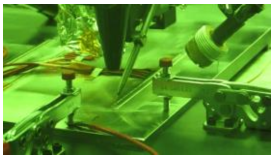
Laser welding model benchmarking testing has been demonstrated





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Design and Construction of A Dedicated Welding Hot Cell at ORNL

- First of its kind in the U.S. Part of a “one-stop” facility for R&D on irradiated materials to support DOE NE programs and industry’s needs.
- Cost-shared with EPRI
- Switchable between different welding processes: laser welding, arc welding, and friction stir welding systems. Both LW and FSW can be remotely operated to reduce contamination issues of welding equipment

Exposed view of concept design of welding hot cell with robotic manipulators and friction stir welding system

Remotely operated friction stir weld (FSW) system to be integrated in the hot cell

Laser welding system under testing and to be integrated in the hot cell

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Decommissioning of Zion Provides a Timely Opportunity to Examine Service-Aged Materials

In support of extended service (and current operations), ORNL is coordinating and contracting activities with Zion Solutions.

In collaboration with the US NRC, EPRI, and others, a list of materials for “harvesting” has been compiled and feasibility examined.

Components of interest:

- **Thru-wall RPV sections**
- **Cabling**
- **Concrete bore samples**

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Advanced Instrumentation, Information, and Control System Technologies

- **Develop, demonstrate, and deploy new digital technologies for instrumentation and control architectures**
- **Provide monitoring capabilities to enhance the continued safe, reliable, and economic operation of the nation's operating nuclear power plants**
- **Develop capabilities to support long-term NPP operations and management**
  - Improve understanding of, confidence in, and facilitate transition to advanced technologies
  - Support development of the technical basis needed to enable technology deployment
- **Key Deliverables (technical reports)**
  - (2012) Mobile technologies for NPP field workers
  - (2014) Advanced alarm management system and advanced control center
  - (2015-2016) Computer-based procedures and an advanced digital architecture for integrating nuclear power plants

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Human Systems Simulation Laboratory (HSSL)

- Reconfigurable environment to develop and validate advanced control center concepts.
- Utilities do not have this capability and are not able to modify their own facilities (control rooms, simulators).
- Support multiple utilities due to the flexibility in configuration.
- Supports rapid prototyping.
- Can easily configure displays and interfaces to replicate an analog, digital, or mixed technology environment.
- Collection of simulation development and testing capabilities.
- Human Performance measurement and data collection facilities.

The HSSL – Human Systems Simulation Laboratory

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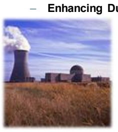
Human Factor Engineering Program

- **Pilot plant project with Duke Energy (formerly Progress Energy) and part of an actual control room upgrade of the Harris and Brunswick nuclear plants (Robinson likely to follow in 2013).**
- **Other major participants are Honeywell, Scientech, and URS Washington.**
  - **Developed a Human Factors Engineering Program in support of control room upgrades modeled on the NRC's NUREG-0711, Human Factors Engineering Program Review Model.**
  - **Delivered Operating Experience Report.**
  - **Delivered a Licensing Basis Report for Control Room Human Factors.**
  - **Conducting Functional Requirements Analysis and Function Allocation.**
  - **Conducting Task Analysis and Operator Sequence Analysis.**
  - **Enhancing Duke's Control Room Human Factors Style Guide.**



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Computer-Based Procedures

- Based on a model of procedure use.
- Includes many features, including:
  - Automatic place-keeping;
  - Built-in functionality to assure procedural adherence;
  - Context sensitivity (aware of external conditions, real-time);
  - Simplified step logic - Conditional steps presented as:
    1. What is the condition?
    2. Instructions based on condition

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Mobile Technologies for NPP Field Workers

- Open architecture – different platforms, different OSs
- Integrates work order, procedures, worker authorization, component verification, clearances, etc.

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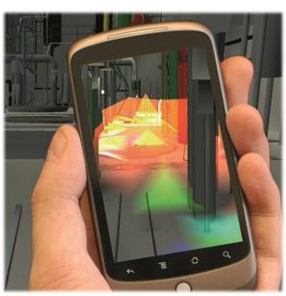
Preview of Augmented Reality: Halden - Handheld Radiation Visualization

- Radiation Calculator adapted from existing tools
- Visualization of facility and radiation
- Uses position tracking and device sensors to know the location and view of the field workers
- Testing in cooperation with EdF R&D



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Outage Safety and Efficiency

- Outage is the largest remaining opportunity to improve capacity factor and nuclear safety margin.
- Outage execution currently makes minimal use of technology in coordinating > 10K plant activities in a span of 3-4 weeks.
- Consists of pilot projects of advanced outage coordination, an advanced outage control center, and outage risk management improvement.
- Provides technology to support real-time status determination and decision making.
- Provides modern outage control centers that are integrated with technology.
- Provides outage risk management technologies to improve control improve work activities interactions with changing plant configurations.
- Pilot Project Completed: Exelon implementing technologies through vendors at 7 units.

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Advanced Outage Coordination

- Real-time collaboration between the OCC and WEC
- Coordination of urgent outage issues and threats
- On-screen markup of outage plans as they are developed

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Transfer of Technology to the Nuclear Power Industry

- Guidelines will be published for each of the areas of enabling capabilities, incorporating the specific technologies and technical reports produced under each of the pilot projects for the respective areas
- EPRI will develop and publish these guidelines, using their standard methods and utility interfaces to develop the documents and validate them with industry
- The LWRS Advanced II&C Pathway will support this effort by providing the relevant information and participating in the development activities
- Results
  - Shift the digital approach from a replacement strategy to a modernization strategy
  - Provide advanced simulation facilities to enable development and validation of advanced control room concepts
  - Transform traditional control rooms to achieve significant operational improvement

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Risk-Informed Safety Margin Characterization (RISMC)

- **Support plant decisions for risk-informed margins management to support improved economics, reliability, and to sustain safety**
- **Goals:**
  - Develop and demonstrate a risk-assessment method coupled to safety margin quantification that can be used by NPP decision makers
  - Create an advanced “RISMC toolkit” that enables more accurate representation of NPP safety margin
- **Key Deliverables:**
  - (2012) Demonstrate the RISMC methodology using a test case based on the Advanced Test Reactor
  - (2013) Demonstrate RELAP-7 boiling water reactor station blackout analysis capability
  - (2015) Enable industry to conduct safety margin quantification

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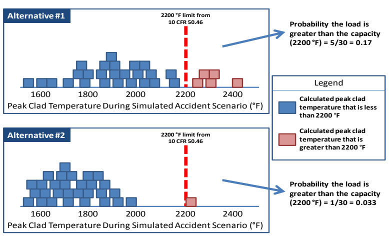
RISMC

- **Loads & capacities are uncertain and can be treated probabilistically**
  - When deterministic margins are evaluated, the analysis is typically very conservative in order to account for uncertainties
- **RISMC uses the probability-margin approach to quantify impacts in order to avoid conservatisms (where possible) and treat uncertainties**



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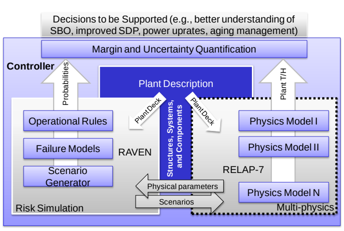
RISMC

Two types of analysis used in RISMC, probabilistic and mechanistic

A blended approach is used where both types of analysis are combined to support a particular decision



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RISMC Tools

- **Margins Analysis Techniques**
  - Develop techniques to conduct margins analysis, including methodology for carrying out simulation-based studies of margin
- **Simulation components of the RISMC Toolkit**
  - RELAP-7 (Systems code that simulates plant behavior)
    - Advanced computational tools and techniques to allow faster and more accurate analysis
  - Simulation Controller (RAVEN – Reactor Analysis and Virtual control Environment)
    - Provides input on plant state to RELAP-7 (including operator actions, component states, etc.)
    - Integrates output from RELAP-7 with other considerations (e.g., probabilistic and procedures information) to determine component states
  - Aging Simulation (Grizzly)
    - Component aging and damage evolution will be modeled in separate modules that will couple to RELAP-7 and RAVEN

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RELAP-7

- **RELAP-7 is a next generation nuclear reactor system safety analysis code**
- **Code is based upon high performance computing (HPC) development and runtime framework – MOOSE (Multi-Physics Object-Oriented Simulation Environment)**
- **RELAP-7 will become main reactor systems simulation toolkit for LWRS/RISMC and next generation tool in the RELAP reactor safety/systems analysis application series (the replacement for RELAP5)**
- **Goal of RELAP-7 development is to leverage 30 years of advancements in software design, numerical integration methods, and physical models**
  - Specifically, the RELAP-7 design is based upon…

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RELAP-7

- **Modern Software Design:**
  - Object-oriented C++ construction provided by the MOOSE framework
  - Designed to significantly reduce the expense and time of RELAP-7 development
  - Designed to be easily extended and maintain
  - Meets NQA-1 requirements
- **Advanced Numerical Integration Methods:**
  - Multi-scale time integration, PCICE (operator split), JFNK (implicit nonlinear Newton method), and a point implicit method (long duration transients)
  - New pipe network algorithm based upon Mortar FEM (Lagrange multipliers)
  - Ability to couple to multi-dimensional reactor simulators
- **State-of-the-Art Physical Models:**
  - All-speed, all-fluid (vapor-liquid, gas, liquid metal) flow
  - Well-posed 7-equation two-phase flow model
  - New reactor heat transfer model based upon fuels performance

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Overarching Goal for RELAP-7: Unified Formulation and Numerical Simulation Methodology

- **Giving capability to simultaneous solve fluid dynamic interface problems as well as multiphase mixtures arising from:**
  - Boiling
  - Flashing or Cavitation
  - Bubble collapse
    - in both high- and low-speed (all-speed) LWR flows
- **Provide highly resolved details where necessary, simultaneously with lesser resolved areas of the simulation.**
- **Using well-posed, physically meaningful, consistent multi-scale models:**
  - Resolve interfaces for larger bubbles in DNS-like (direct numerical simulation) manner – single velocity, single pressure
  - Homogenize or average the two-phase flow field for smaller bubbles – two velocities, two pressures

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RAVEN: Tasks Definition

R
A
V
E
N

Controls (historic/design basis event coordinator)

Control Logic | Operator Response

Risk Informed Safety Margins Characterization

Monte Carlo | Event Trees | Data Analysis

Graphical Pre and Post Processing

CAD Input | 3-D Visualization | GUI

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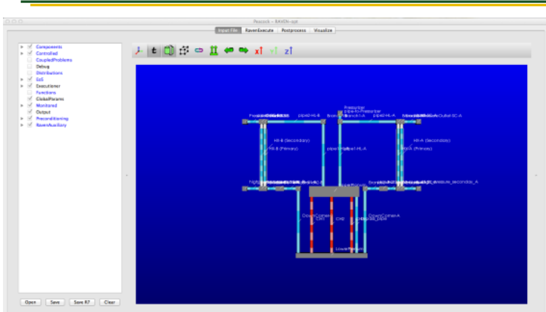
Prototype used to define the 3D geometry



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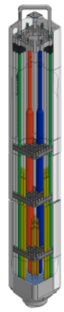
Advanced Nuclear Fuels

- **Improve scientific knowledge basis for understanding and predicting fundamental nuclear fuel and cladding performance in nuclear power plants**
- **Apply information to development of high-performance, high burn-up fuels with improved safety, cladding integrity, and improved nuclear fuel cycle economics**
- **Focus of this pathway is development of silicon carbide (SiC) ceramic matrix composites (CMC) nuclear fuel cladding**
  - Allows significantly improved cladding performance at very high accident temperatures and greatly reduced chemical reactivity with reactor cooling water
  - This technology has the potential to provide a very large safety margin increase and economic benefit compared to other new technologies or evolutionary advances in existing technology



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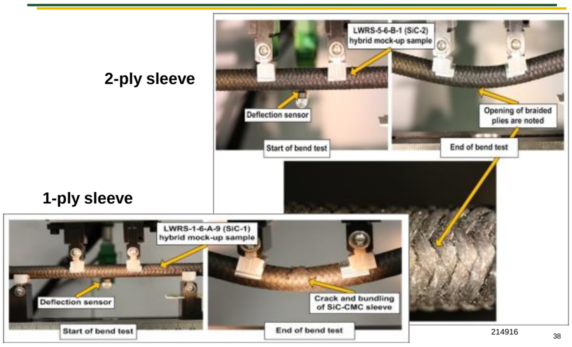
SiC Cladding Bend Testing



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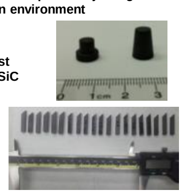
Industry Activities: SiC / SiC Joining

Reliable SiC/SiC joints that can withstand neutron irradiation represent a key technical gap for use of SiC composites in nuclear fuel cladding

Competitively awarded industry contracts established to develop robust joining techniques for SiC structures that can withstand radiation environment

General Atomics:
GA will perform research to produce a mechanically robust and impermeable joining between an end plug and a SiC-SiC tube representative of an LWR SiC- SiC clad fuel rod for subsequent irradiation testing under conditions representative of an LWR core environment.



HyperTherm Corporation:
HTC will examine two promising SiC joining techniques with respect to SiC matrix fuel cladding end close-out including an optimization of joint design. Evaluations will include mechanical, microstructural and hermeticity measurements.